Catadioptric projection objective with geometric beam splitting

This is a Continuation-in-Part Application of pending prior Application No. 09/751,352, filed December 27, 2000. The present Application additionally claims benefit of Provisional Application No. 60/511,673, filed October 17, 2003

BACKGROUND OF THE INVENTION
Field of the invention

[01] The invention relates to a catadioptric projection objective for projecting a pattern arranged in an object plane of the projection objective into an image plane of the projection objective with the formation of at least one real intermediate image at an image-side numerical aperture NA > 0.7.

[02] <u>Description of the related prior art</u>

[03] Projection objectives of this type are used in microlithography projection exposure systems for producing semiconductor components and other finely structured components. They are used to project patterns of photo masks or engraved plates, which in the following text will generally be designated masks or reticles, onto an object coated with a light-sensitive layer, with extremely high resolution on a reducing scale.

[04] In this case, in order to generate finer and finer structures, it is necessary, firstly, to enlarge the image-side numerical aperture NA of the projection objective and, secondly, to use shorter and shorter wavelengths, preferably ultraviolet light with wavelengths of less than about 260 nm, for example 248 nm, 193 nm or 157 nm.

[05] For wavelengths down to 193 nm, it is possible to operate with purely refractive (dioptric) projection systems, whose production can be managed easily because of their rotational symmetry about the optical axis. In order to achieve extremely small resolutions, however, it is necessary here to operate with extremely large numerical apertures NA of more than 0.8 or 0.9. In the case of dry systems with an adequately large, finite working distance (distance between the exit face of the objective and the image plane), these can be implemented only with difficulty. Refractive immersion systems have also already been proposed which, by using an immersion liquid of high refractive index between objective exit and image plane, permit values of NA > 1.

[06] For the aforementioned short wavelengths, however, it becomes more and more difficult to provide purely refractive systems with adequate correction of color errors (chromatic aberration), since the Abbé constants of suitable transparent materials are relatively close to one another. Therefore, for extremely high resolution projection objectives, use is predominantly made of catadioptric systems, in which refractive and reflective components, in particular therefore lenses and refractive mirrors, are combined.

[07] When using projecting reflecting surfaces, it is necessary to use beam deflection devices if obscuration-free and vignetting-free projection is to be obtained. Both systems with geometric beam splitting by means of one or more wholly reflecting folding mirrors (deflection mirrors) and systems with physical beam splitting are known. Furthermore, planar mirrors can be used for folding the beam path. These are generally used in order to meet specific installation space requirements or in order to align the object and image plane parallel to each other. These folding mirrors are optically not absolutely necessary.

[08] The use of a physical beam splitter, for example in the form of a beam splitter cube (BSC), with polarization-selective beam splitter surface makes it possible to implement projection objectives with an object field centered on the optical axis (one-axis systems). The disadvantage with such systems is that suitable transparent materials for the production of a beam splitter cube are available only to a limited extent in the required large volumes. In addition, the production of the polarization-selectively effective beam splitter layers presents considerable difficulties. An incomplete polarization-selective action can lead to the production of leakage transmission dependent on the angle of incidence and therefore to intensity inhomogeneities in the projection.

[09] The disadvantage of systems with polarization-selective beam splitters can largely be avoided in systems with geometric beam splitting, that is to say when wholly reflective folding mirrors are used in the beam deflection device. Such a folding mirror permits the optical path leading to a concave mirror to be separated physically from the optical path leading away from the concave mirror. Many problems which can result from the use of polarised light are eliminated.

[010] In the case of projection objectives with geometric beam splitting, various folding geometries are possible, there being specific advantages and disadvantages, depending on the course of the light path between object field and image field.

[011] US patent 6,195,213 B1 shows various embodiments of projection objectives with geometric beam splitting for projecting a pattern of a mask arranged in an object plane of the projection objective into an image plane of the projection objective with

the formation of a single, real intermediate image. The projection objectives, which reach image-side numerical apertures up to NA = 0.75, have a catadioptric first objective part, which is arranged between the object

5   plane and the image plane and has a concave mirror and a beam deflection device, and also a dioptric second objective part, which is arranged between the first objective part and the object plane. The elements of the first objective part used for forming the

10 intermediate image are designed in such a way that the intermediate image lies optically and geometrically in the vicinity of the first folding mirror. The beam deflection device has a first folding mirror, which is arranged in the beam path between the concave mirror

15 and the image plane. In these systems, the first folding mirror is arranged in such a way that light coming from the object plane falls firstly on the concave mirror of the first objective part before it is reflected by the latter to the first folding mirror.

20 From the latter, it is deflected by 90° and reflected to a second folding mirror, which deflects the radiation coming from the first folding mirror once more through 90° in the direction of the image plane. This beam guidance leads to an h-shaped structure of

25 the system, for which reason this folding geometry is also designated h-folding. The projection objective has only one concave mirror.

[012]   Accommodated in the space between object plane

30 and first folding mirror are a plurality of lenses used for the optical correction. The region between the folding mirrors is free of lenses, which is intended to permit a compact design. Therefore all the lenses and the concave mirror are arranged in objective parts

35 which can be aligned vertically, which is intended to achieve a structure which is stable with respect to the influences of gravity.

[013]   In US patent 5,969,882 (corresponding to EP-A-
0 869 383), other projection objectives with h-folding
and only one concave mirror are described, in which
lenses are arranged in the space between object plane
5   and first folding mirror. In embodiments in which the
first and the second folding mirror are configured as
reflective surfaces of a deflection prism, the region
between the folding mirrors is free of any refractive
power.
10

[014]   European patent EP 0 604 093 B1 and US patent
5,668,673 connected thereto via a common priority show
catadioptric projection objectives with relatively low
numerical apertures of NA ≤ 0.5, in which the object
15   field is projected into the image field with the aid of
two concave mirrors, forming a single real intermediate
image.   Embodiments with different, partly complex
folding geometries are shown, in some embodiments a
first beam section running from the object plane to a
20   concave mirror and a second beam section running from
this concave mirror to the image plane crossing. The
complex folding geometries with a large number of
optical components physically close to one another mean
that considerable mechanical and mounting problems may
25   be expected in the practical implementation of such
designs.   A transfer of the design concepts into the
area of higher numerical apertures appears not to be
practical, on account of the associated greater maximum
beam diameters and the correspondingly increasing
30   maximum lens diameters.

[015]   EP-A-0 889 434 (corresponding to US Serial No.
09/364382) shows projection objectives with a beam
deflection device formed as a mirror prism. The mirror
35   prism forms the first folding mirror for the deflection
of the radiation coming from the object plane to the
concave mirror, and a second folding mirror for the
deflection of the radiation reflected from the concave
mirror to the second objective part, which contains

only refractive elements. The catadioptric first
objective part forms a real intermediate image, which
is located freely accessibly at a distance behind the
second reflecting surface. The single concave mirror
is fitted in a side arm of the projection objective
which projects transversely with respect to the
vertical direction when installed and which is also
designated a "horizontal arm" (HOA). On account of the
1-form geometry of the beam path, such a folding
geometry is also designated "1-folding".   Other
projection objectives with only one concave mirror and
1-folding are described, for example, in DE 101 27 227
(corresponding to US patent Application US 2003/021040)
or the international patent Application WO 03/050587.

[016]   Systems with geometric beam splitters have the
disadvantage, caused by the principle, that the object
field is arranged eccentrically with respect to the
optical axis (extra-axial system or off-axis system).
This places high requirements on the correction of
image errors since, in such a projection system, as
compared with on-axis systems, a larger usable field
diameter has to be corrected adequately with the same
object field size. This larger field area, including
the object field, will also be designated the
"superfield" in the following text.

[017]   Optimization of the size of the superfield
becomes more and more difficult as the numerical
aperture of the projection objective increases, since
the clearances for the arrangement and dimensioning of
optical components and here, in particular, the folding
mirror, become smaller and smaller, with the limiting
condition of vignetting-free projection. In addition,
the mechanical mounting of the optical components
increasingly presents difficulties the more complex
their relative arrangement to one another is.

SUMMARY OF THE INVENTION

[018]   It is an object of the invention to provide catadioptric projection objectives which, with a finite working distance, permit a higher projection quality, even at extremely high numerical apertures.   In this case, a beneficial geometry for stable mounting of optical components is to be achieved.   In particular, an increase in the image-side numerical aperture in regions of $NA \geq 0.8$ or $NA \geq 0.9$ is to be made possible which, when such projection objectives are used in immersion lithography or in near field lithography, permit usable numerical apertures of $NA \geq 1$.

[019]   As an achievement of this object, according to one formulation of the invention, the invention provides a catadioptric projection objective for projecting a pattern arranged in an object plane of the projection objective into an image plane of the projection objective, in which at least one real intermediate image is formed during the projection and an image-side numerical aperture of $NA > 0.7$ is achieved.   The projection objective comprises:
an optical axis; and
at least one catadioptric objective part that comprises a concave mirror and a first folding mirror;
wherein a first beam section running from the object plane to the concave mirror and a second beam section running from the concave mirror to the image plane can be generated;
and the first folding mirror is arranged with reference to the concave mirror in such a way that one of the beam sections is folded at the first folding mirror and the other beam section passes the first folding mirror without vignetting, and the first beam section and the second beam section cross one another in a cross-over region.

[020]   The crossed beam guidance in the region of the catadioptric objective part permits projection objectives with a compact and mechanically stable arrangement of the optical components.   In this case, vignetting-free beam guidance can be achieved, so that no folding mirror cuts a beam which is reflected either at the folding mirror or is led past the folding mirror without reflection.   In this way, only the system aperture stop limits, in an axially symmetrical way, the angular distribution of the beams which contribute to the imaging. At the same time, even at extremely high numerical apertures, which are associated with large maximum beam diameters and possibly highly convergent or divergent beams in the region of field planes, a moderate size of the superfield to be corrected can be achieved.

[021]   The invention can be used in different folding geometries.   In some embodiments, the first folding mirror is arranged such that the first beam section is folded at the first folding mirror and the second beam section passes the first folding mirror without vignetting.   In this case, the first folding mirror typically has a reflecting surface facing away from the optical axis. This beam guidance, in which the radiation running indirectly or directly from the object plane to the catadioptric objective part strikes the first folding mirror first, is typical of objectives with the 1-folding mentioned at the beginning.

[022]   In other embodiments, the first folding mirror is arranged such that the first beam section, that is to say the radiation coming directly or indirectly from the object plane, passes the first folding mirror without vignetting and the second beam section, that is to say the radiation reflected by the concave mirror, is folded at the first folding mirror. Here, the first folding mirror can have a reflecting surface facing the

optical axis, so that the radiation on the path from the concave mirror to objective parts arranged downstream and to the image plane crosses the optical axis and the first beam section. This beam guidance is typical of the h-designs mentioned at the beginning.

[023] In many advantageous embodiments, the projection objective has only a single concave mirror. However, embodiments with more than one concave mirror are also possible. Such embodiments can contain a plurality of catadioptric objective parts, of which one or more can have the crossed beam guidance.

[024] It may be beneficial if the projection objective has at least one second folding mirror in addition to the first folding mirror. Additional folding mirrors can be used for the purpose of aligning object plane and image plane parallel to each other. Additional folding mirrors are also required when further catadioptric objective parts with geometric beam splitting are provided. Within the scope of the invention, there are embodiments with one or more catadioptric objective parts.

[025] The first and the second folding mirrors can be fitted to a common carrier. The first and the second folding mirrors are preferably separate folding mirrors, which are mounted in separate mounts and, if appropriate, can be set or adjusted separately from one another. The folding mirrors can be fitted on different sides of the optical axis. The folding mirrors can be fixed stably on mutually opposite sides of the mount construction of the projection objective with the aid of compact fixing constructions. A separate mounting of the folding mirrors can also be advantageous with regard to the fact that, as a rule, only one of the mirror edges is critical with regard to the vignetting of the beam. These can be positioned

beneficially given separate mounting of folding mirrors.

[026] Projection objectives according to the invention can have one or more real intermediate images. In the region of an intermediate image there exists a local minimum of the beam diameter, so that it is generally beneficial to fit a folding mirror geometrically and/or optically in the vicinity of an intermediate image. In one embodiment, the first folding mirror has an inner mirror edge near the optical axis and an intermediate image is arranged in the geometric vicinity of the inner mirror edge. The intermediate image can be the single intermediate image of the projection objective, which preferably has a beam folding geometry typical of 1-folding. The geometric distance between the intermediate image and the inner mirror edge is preferably less than 30% or less than 20% or less than 10% of the meridional extent of the intermediate image.

[027] In some embodiments, in particular in embodiments with 1-folding, the first folding mirror has an inner mirror edge near the optical axis, and an intermediate image is arranged in a geometric space between the inner mirror edge and the object plane. In these embodiments, it is possible for the beam to be "forced through" between the first folding mirror and the field plane placed geometrically upstream of the latter and/or an optical component placed geometrically upstream of the folding mirror without vignetting.

[028] In some embodiments, the upstream field plane is the object plane. In other embodiments, one or more refractive and/or catadioptric projection systems can be connected upstream of the catadioptric objective part which has the crossed beam guidance, so that the upstream field plane is an intermediate image plane of the projection objective.

[029]   It can be beneficial if the at least one intermediate image is arranged in the optical vicinity of a folding mirror. An optical vicinity of a folding mirror is characterized in particular by the fact that neither lens nor any other optical element is arranged between the intermediate image and the most closely situated folding mirror.   Sometimes, an intermediate image is arranged in the optical vicinity of a second folding mirror, not necessary for the beam separation. An arrangement of an intermediate image such that at least part of the intermediate image falls on a reflecting surface of a folding mirror should be avoided, on the other hand, since this can lead to errors which may be present in the reflecting surface being projected sharply into the image plane.   A spacing between intermediate image and reflecting surface is therefore advantageous.

[030]   One class of projection objectives according to the invention has only a single real intermediate image as well as a single concave mirror and two folding mirrors, which are aligned for parallel alignment of object plane and image plane.   In this case, both h-folding and l-folding are possible.

[031]   Other embodiments have two or more real intermediate images, in particular at least three real intermediate images.   Embodiments having at least three real intermediate images have a first objective part for projecting the object field into a first real intermediate image, a second objective part for forming a second real intermediate image with the radiation coming from the first objective part, a third objective part for forming a third real intermediate image from the radiation coming from the second objective part, and a fourth objective part for projecting the third real intermediate image into the image plane.

[032]   In preferred systems, the third intermediate image is projected into the image plane directly, that is to say without the formation of further intermediate images, so that there are precisely three real intermediate images.

[033]   The first objective part can serve as a relay system, in order to form a first intermediate image with a predefinable correction state at a suitable position from the radiation coming from the object plane.

[034]   At least two of the objective parts are preferably catadioptric and in each case have a concave mirror.   In particular, precisely two catadioptric objective parts can be provided.

[035]   In one development, the second objective part and the third objective part are constructed with one concave mirror in each case. Each of the concave mirrors is assigned a folding mirror, in order either to deflect the radiation to the concave mirror or to deflect the radiation coming from the concave mirror in the direction of a following objective part.

[036]   The fourth objective part is preferably purely refractive and can be optimized in order to produce high image-side numerical apertures (NA).

[037]   Preferred embodiments comprise four objective parts, which are grouped in a cross-like arrangement wherein, at one or more points of the complexly folded beam path, cross-over regions can arise in which the first beam section running from the object plane to a concave mirror and the second beam section running from the concave mirror to the image plane cross one another.

[038]   The provision of at least two catadioptric
subsystems has great advantages.   In order to see
substantial disadvantages of systems with only one
catadioptric subsystem, it is necessary to consider
how, in a catadioptric objective part, the correction
of the Petzval sum and of the chromatic aberrations is
carried out.   The contribution of a lens to the
longitudinal chromatic aberration CHL is given by

$$CHL \propto h^2 \cdot \varphi \cdot \nu$$

that is to say it is proportional to the marginal beam
height h (as the square), the refractive power φ of the
lens and the dispersion ν of the material.   On the
other hand, the contribution of a surface to the
Petzval sum depends only on the surface curvature and
the refractive index step (which is -2 in the case of a
mirror).

[039]   In order to allow the contribution of the
catadioptric group to the chromatic correction to
become large, large marginal beam heights are therefore
needed (that is to say large diameters); in order to
allow the contribution to the Petzval correction to
become large, large curvatures (that is to say small
radii, which are most expediently achieved with small
diameters).   These two requirements oppose each other.

[040]   The opposing requirements for Petzval
correction (that is to say correction to the curvature
of the image field) and chromatic correction can be
solved by the introduction of (at least) a further
catadioptric part into the system.

[041]   The two catadioptric systems can be designed
asymmetrically in such a way that one has a trend to a
large diameter with flat radii for CHL correction and
the other has a trend to a small diameter with curved
radii for Petzval correction.   A symmetrical structure

is likewise possible and can be beneficial from the point of view of simple fabrication.

[042]   In general, the degree of freedom consists in distributing the correction of these and other image errors uniformly or nonuniformly to two (or more) catadioptric subsystems. In this way, with a structure on which the requirements are relaxed, extremely high apertures with an excellent state of correction can be implemented.

[043]   The invention makes it possible to provide catadioptric projection objectives in which, even at extremely high numerical apertures, the geometric optical conductance to be corrected does not become too high. The geometric optical conductance (or etendue) is defined here as the product of the image-side numerical aperture and the field size. In some embodiments, a diagonal ratio between the length of the diagonal of a minimum circle centered on the optical axis and enclosing the object field (superfield diagonal) and the length of a diagonal of the object field is less than 1.5, in particular less than 1.4 or less than 1.3 or less than 1.2.

[044]   The invention makes it possible to provide easily correctable catadioptric projection objectives which, with a compact design and mechanically stable structure, can achieve extremely high numerical apertures. There are embodiments which are designed as "dry objectives". Dry objectives are distinguished by the fact that they are designed for the purpose in which, between the exit side of the projection objective and an input coupling surface of an object to be exposed, for example a wafer, there is in operation a gap which is filled with gas and whose gap width is typically considerably larger than the working wavelength. In such systems, the numerical apertures that can be achieved are restricted to values NA < 1

since, as the value NA = 1 is approached, total
reflection conditions occur at the exit face, which
prevent illuminating light being coupled out of the
exit face.   The image-side numerical aperture in
5   preferred embodiments of dry systems is NA > 0.8, even
NA ≥ 0.85 or NA ≥ 0.9 being possible.

[045]   Within the scope of the invention, catadioptric
projection objectives which are designed as immersion
10 objectives are also possible. In the case of immersion
lithography, as is known, the achievable resolution of
an exposure process is improved by the fact that an
immersion medium with high refractive index is
introduced into the space between the last optical
15 element of the projection objective and the substrate,
for example an immersion liquid which has a refractive
index $n_I ≥ 1.3$ at the working wavelength. As a result,
projection objectives or projections with an image-side
numerical aperture NA > 1.0 are possible, preferably NA
20 ≥ 1.1 or NA ≥ 1.2 or NA ≥ 1.3 being possible.

[046]   The optical structure also permits use for non-
contact near-field projection lithography.   In this
case, coupling of sufficient light energy into the
25 substrate to be exposed via a gap filled with the gas
is possible if a sufficiently low image-side working
distance is maintained on average over time.   This
distance should lie below four times the working
wavelength used, in particular below the working
30 wavelength. It is particularly beneficial if the
working distance is less than half the working
wavelength, preferably less than one third, one quarter
or one fifth of the working wavelength. At these short
working distances, projection in the optical near field
35 can be carried out, in which evanescent fields, which
exist in the immediate facility of the last optical
face of the projection system, are used for the
projection.

[047]   The invention therefore also comprises a non-contact projection exposure method in which evanescent fields of the exposure light, which are found in the immediate vicinity of the exit face, are made useful to the lithographic process.   In this case, at sufficiently low (finite) working distances, in spite of geometric total reflection conditions at the last optical face of the projection objective, a proportion of light that can be used for lithography is coupled out of the exit face of the objective and coupled into an input coupling surface immediately adjacent at a distance.

[048]   Embodiments   for   non-contact   near   field projection lithography have preferably typical working distances in the range of the working wavelength or less, for example between about 3 nm and about 200 nm, in particular between about 5 nm and about 100 nm. The working distance should be matched to the other properties of the projection system (properties of the projection objective close to the exit face, properties of the substrate close to the input coupling surface) such that, on average over time, an input coupling efficiency of at least 10% is achieved.

[049]   Within the scope of the invention, a method for producing semiconductor components and the like is thus possible, in which a finite working distance between an exit face for exposure light assigned to the projection objective and an input coupling surface for exposure light assigned to the substrate is set, the working distance being set within an exposure time interval at least temporarily to a value which is smaller than a maximum extent of an optical near field of the light emerging from the exit face.

[050]   The above and further features also emerge from the description and from the drawings, as well as from the claims, it being possible for the individual

features, in each case on their own or in a plurality, to be implemented in the form of sub-combinations in an embodiment of the invention and in other fields and for them to represent embodiments that are advantageous and intrinsically capable of protection.

BRIEF DESCRIPTION OF THE DRAWINGS

[051]   Fig. 1 shows a schematic representation of a projection exposure system for immersion lithography with an embodiment of a catadioptric projection objective according to the invention;

fig. 2   is a lens section through a first embodiment of a catadioptric immersion objective according to the invention with geometric beam splitter and 1-folding;

fig. 3   is a schematic diagram which shows a rectangular object field arranged eccentrically in relation to the optical axis and a circular superfield to be corrected;

fig. 4   shows the projection objective shown in fig. 2 in an illustration suitable for comparison with fig. 5;

fig. 5   shows a catadioptric projection objective with the same optical structure as in fig. 4 but with a conventional geometric beam splitter;

fig. 6   shows a further embodiment of a catadioptric projection objective with a geometric beam splitter and 1-folding, which is designed for non-contact near field lithography;

fig. 7   shows a detailed view of the region of folding mirrors of another embodiment of a catadioptric projection objective according to the invention with geometric beam splitting;

fig. 8   shows an embodiment of a catadioptric dry objective with geometric beam splitting and h-folding according to an embodiment of the invention;

fig. 9a shows an embodiment of an immersion projection objective according to the invention having two intermediate images with a cross shape and asymmetrical structure of two catadioptric objective parts;

fig. 9b shows a detailed view of the folding device in fig. 8;

fig. 10 shows a variant of the system shown in fig. 9a with oblique horizontal arms;

fig. 11 shows an embodiment of a dry system according to the invention having three intermediate images and a cross shape;

fig. 12 shows a folding device with prism;

fig. 13 shows another embodiment of a projection objective built up in a cross shape with a largely symmetrical structure;

fig. 14 shows a further embodiment of a projection objective according to the invention with a relay system arranged between two catadioptric objective parts;

fig. 15 shows an embodiment of a projection objective according to the invention with decoupled optical axes of the catadioptric objective parts;

fig. 16 shows a further embodiment of a projection objective according to the invention with decoupled optical axes of the catadioptric objective parts.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[052]   In the following description of preferred embodiments, the term "optical axis" designates a straight line or a series of straight line sections through the centers of curvature of the optical components.   The optical axis is folded at folding mirrors (deflection mirrors) or other reflective surfaces.   Directions and distances will be described as "image-side" if they are oriented in the direction of the image plane or of the substrate to be exposed and located there, and as "object-side" if they are oriented toward the object plane or a reticle located there with reference to the optical axis.   In the examples, the object is a mask (reticle) having a pattern of an integrated circuit, it can also be another pattern, for example a grating.   In the examples, the image is projected onto a wafer provided with a photoresist layer which acts as a substrate; other substrates, for example elements for liquid crystal displays or substrates for optical gratings, are also possible.

[053]   In fig. 1, a micro lithographic projection exposure machine in the form of a wafer stepper 1, which is provided for the production of highly integrated semiconductor components by means of immersion lithography, is shown schematically.   The projection exposure machine 1 comprises, as light source, an excimer laser 2 having a working wavelength of 193 nm, other working wavelengths, for example 157 nm or 248 nm, also being possible.   An illumination system 3 connected downstream produces in its exit plane 4 a large, sharply delimited, very homogeneously illuminated illumination field matched to the telecentering requirements of the projection objective 5 connected downstream.   The illumination system 3 has devices for selecting the illuminating mode and, in the example, can be switched over between conventional

illumination at a variable level of coherence, annular field illumination and dipole or quadrupole illumination.

5   [054]   Arranged behind the illumination system is a device 40 (reticle stage) for holding and manipulating a mask 6 such that the latter lies in the object plane 4 of the projection objective 5 and can be moved in this plane in a removal direction 7 (y direction) for

10   scanning operation.

[055]   Behind the plane 4, also designated the mask plane, there follows the catadioptric reduction objective 5, which projects an image of the mask with a

15   reduced scale of 4:1 onto a wafer 10 covered with a photoresist layer. Other reduction scales, for example 5:1 or 10:1 or 100:1 or less are likewise possible. The wafer 10 serving as light-sensitive substrate is arranged such that the flat substrate surface 11 with

20   the photoresist layer substantially coincides with the image plane 12 of the projection objective 5. The wafer is held by a device 50 (wafer stage), which comprises a scanner drive in order to move the wafer synchronously with the mask 6 and parallel to the

25   latter. The device 50 also comprises manipulators in order to move the wafer both in the z direction parallel to the optical axis 13 of the projection objective and in the x and y direction at right angles to this axis. A tilting device having at least one

30   tilt axis running at right angles to the optical axis 13 is integrated.

[056]   The device 50 provided for holding the wafer 10 is constructed for use in immersion lithography. It

35   comprises a holding device 15 which can be moved by a scanner drive and whose base has a flat recess to hold the wafer 10. By means of a circumferential edge 16, a flat liquid-tight holder that is open at the top is formed for a liquid immersion medium 20, which can be

introduced into the holder by devices not shown and can
be led away from said holder. The height of the edge is
dimensioned such that the immersion medium put in can
cover the surface 11 of the wafer 10 completely and,

5   when the working distance between the objective exit
and wafer surface is set correctly, the exit-side end
region of the projection objective 5 can dip into the
immersion liquid.

10   [057]   Fig. 2 shows the first embodiment of a
catadioptric reduction objective 100 designed for
immersion lithography and having geometric beam
splitting.   It is used to project a pattern of a
reticle or the .like arranged in its object plane 101
15   into an image plane 103 aligned parallel to the object
plane on a reduced scale, for example in the ratio 4:1,
with the formation of a single real intermediate image
102. Between the object plane 101 and the image plane
103, the objective has a catadioptric objective part
20   104, which comprises a concave mirror 105 and a first,
flat folding mirror 106, and also a purely refractive
dioptric objective part 107 following behind the
catadioptric objective part in the light path. Between
the intermediate image 102 and the first lens of the
25   refractive objective part 107 there is arranged a
second folding mirror 108, whose reflecting surface
lies in a plane which is aligned at right angles to the
plane of the reflective surface of the folding mirror
106.   The first folding mirror 106 has a reflecting
30   surface which predominantly faces away from the optical
axis 110 and which is used to deflect the radiation
coming from the. object plane in the direction of the
concave mirror 105. The second folding mirror 108,
which is situated geometrically closer to the object
35   plane 101 than the first folding mirror 106, is
arranged and aligned such that it deflects the
radiation coming from the concave mirror in the
direction of the image plane 103.   While the first
folding mirror 106 is necessary for the beam deflection

toward the concave mirror 105, the second folding mirror 108 can also be omitted. Then, without further deflection mirrors, the object plane and the image plane would be substantially at right angles to each
5   other.

[058]   The first folding mirror 106 is inclined with respect to the optical axis 110 at an angle of inclination of about 40°, so that the side arm
10   (horizontal arm, HOA) of the projection objective, bearing the concave mirror 105, is inclined at about 100° with respect to the parts of the optical axis that are at right angles to the object and image plane. This ensures that the region of the concave mirror does
15   not project into the region of the devices provided to hold the reticle.

[059]   A first beam section 120 leads from the object plane 101 to the concave mirror 105 and is folded at
20   the first folding mirror 106. A second beam section 130 leads from the concave mirror 105 to the image plane 103 and is folded at the second folding mirror 108. The intermediate image 102 is located in the immediate vicinity of the inner mirror edge 115, close to the
25   optical axis 110 and facing the object plane 101, of the first folding mirror in the space between the inner mirror edge 115 and the reticle plane, beneficially in such a way that the beam of the second beam section, converging toward the intermediate image 102 and
30   diverging again behind the latter, can pass through the first folding mirror without being cut. As can be seen from fig. 2, in this case the minimum geometric distance between the inner mirror edge 115 and the beam in the region of the intermediate image is considerably
35   smaller than the diameter of the intermediate image lying in the section plane of the illustration and is less than about 20% of this diameter. Since the projection scale of the first projection system comprising the catadioptric objective part, which forms

the intermediate image, is close to β = 1, this diameter corresponds substantially to the width of the object field in the removal direction or scanning direction 7 (y direction). From an optical point of view, the intermediate image 102 lies in the immediate vicinity of the second folding mirror 108, no lens being arranged between the intermediate image and the second folding mirror.

[060]   The projection objective 100 represents an advantageous variant of the 1-folding explained at the beginning, in which the intermediate image lies geometrically between the object plane or the reticle and the first folding mirror 106 and the beam deflection is carried out with the aid of two separate mirrors. Further below, it will be explained in more detail how, as a result of this unusual folding arrangement, the optical conductance to be corrected or the superfield size of the entire system can be kept small, even in the case of extremely high numerical apertures.

[061]   During operation of the projection system, the light from the illumination system enters the projection objective on the side of the object plane 101 facing away from the image and passes first of all through the mask arranged in the object plane. The transmitted light then passes through a plane-parallel entry plate 151 and a positive meniscus lens 152 with a concave surface on the image side, designed as a half-lens, arranged between said entry plate and the first folding mirror. Following deflection at the first folding mirror 106, a positive meniscus lens 153 arranged between folding mirror and concave mirror in the vicinity of the first folding mirror and having a spherical, concave entry face which is opposite the folding mirror and an aspherical exit face, is passed through before a mirror group 175 is reached. The mirror group 175 comprises two negative meniscus lenses

154, 155 which are placed immediately before the
concave mirror 105 and whose convex or elevated surface
in each case points toward the concave mirror 105, and
the concave mirror 105 itself. The light reflected from
5   a concave mirror 105 and led back through the lenses
155, 154 and 153, which are passed twice, then forms
the real intermediate image 102 in the immediate
vicinity of the mirror edge 115, facing the object, of
the first folding mirror.

10

[062]   The lenses of the refractive objective part 107
can be subdivided functionally into a transfer group T
and a focusing group F and are used jointly to project
the intermediate image produced immediately in front of
15   the second folding mirror 108 into the image plane 103
on a reduced scale. The transfer group comprises three
biconvex positive lenses 156 to 158 following one
another directly and a following negative meniscus lens
159 with an object-side concave face.

20

[063]   The focusing group, following at a distance,
opens with a biconcave negative lens 160 with a highly
negative refractive power, which effects a high amount
of beam widening and, because of the high angle of
25   incidence of the radiation on its exit side,
contributes effectively to the correction of image
errors. The three following positive lenses 161, 162,
163 having aspherical entry faces and spherical exit
faces initiate the beam convergence. In the region of
30   the system aperture stop 180 there is situated a
negative meniscus 164 with an image-side concave face.
This is followed by only positive lenses 165 to 169,
which are substantially used to produce the high image-
side numerical aperture.   The last optical element
35   before the image plane 103 is formed by a plane-convex
lens 169, whose flat exit side is situated at a working
distance of 2 mm in front of the image plane 103. In
operation, the narrow opening is filled with an
immersion medium 190. In the example, extremely pure

water with a reflective index $n_I = 1.437$ (193 nm) is used as immersion liquid.

[064]   The specification of the design is summarized in table 1 in tabular form.   In this case, column 1 specifies the number of the refractive, reflective or otherwise distinguished face, column 2 the radius r of the face (in mm), column 3 the distance d, designated the thickness, from the face to the following face (in mm), column 4 the material of a component and column 5 the refractive index of the material of the component which follows the specified entry face. Column 6 shows the maximum usable half-diameter in mm.   The overall length L of the objective between object and image plane is about 930 mm.

[065]   In the embodiment, nine of the faces, namely the faces 5, 8 = 19, 10 = 17, 12 = 14, 27, 33, 35, 37 and 47 are aspherical.   Table 2 specifies the corresponding asphere data, the heights of the meniscuses of the aspherical faces being calculated in accordance with the following rule:

$$p(h)=[((1/r)h^2)/(1+SQRT(1-(1+K)(1/r)^2h^2))]+C1*h^4+C2*h^6+...$$

[066]   Here, the reciprocal (1/r) specifies the radius of curvature of the face at the vertex of the face, and h the distance of a point on the face from the optical axis.   Thus, p(h) specifies this meniscus height, that is to say the distance of the point of the face from the vertex of the face in the z direction, that is to say in the direction of the optical axis.   The constants K, C1, C2,... are reproduced in table 2.

[067]   The immersion system 100 is designed for a working wavelength of about 193 nm, at which the synthetic quartz glass (SiO_2) used for all the lenses has a refractive index n = 1.5602.   It is matched to extremely pure water as immersion medium (n_I = 1.4367

at 193 nm) and has an image-side working distance of 2 mm. The image-side numerical aperture NA is 1.1, the projection scale is 4:1. The system is designed for an image field with a size of 26 × 5.5 mm^2 and is doubly

5   telecentric. The diagonal ratio between the length of a diagonal of a minimum circle centered on the optical axis and enclosing the object field and the length of a diagonal of the object field (cf. fig. 3) is about 1.26.

10

[068]   Some special features of the projection objective will be explained in more detail by using figures 3 to 5. In this case, fig. 3 shows a schematic representation of the dimensioning of object field and

15   superfield in the object plane of the projection objective, fig. 4 a folding geometry in the case of a projection objective according to the invention with a geometric beam splitter and 1-folding (cf. fig. 2), and fig. 5 a schematic representation of the beam course

20   and the folding geometry in the case of a similar projection objective without a crossed beam path.

[069]   On account of the geometric beam splitting, the projection objective has an extra-axially arranged

25   object field 200, there being a finite object field distance h between the optical axis 210 and the object field. The object field of the wafer scanner is rectangular or slot-like with a high aspect ratio and is identified by the length of its diagonal 201 (slot

30   diagonal). In order to be able to project this extra-axial object field with little aberration, it is necessary to correct the projection objective for a field size which is considerably larger than the object field itself. This circular superfield 202 which is

35   enclosed by a minimum circle about the eccentric object field centered around the optical axis 210, can be defined by the length of its diagonal 203, which is designated the superfield diagonal here. It can be seen by those skilled in the art that the diagonal

ratio between the length of the superfield diagonal and
the length of the slot diagonal should lie as close as
possible to 1 in order to have the lowest possible
effort on correction in the case of an extra-axial

5   object field.

[070]   By using figures 4 and 5, the problem in
minimizing the optical conductance and the superfield
diameter and the problem of adequate space in the

10   vicinity of the folding mirror will be explained by
means of a comparison between conventional 1-folding
with two folding mirrors fitted to a mirror prism (fig.
5) and an embodiment according to the invention with
separate folding mirrors (fig. 4). In this case, fig. 4

15   corresponds to the objective structure shown in fig. 2.
In both the folding variants illustrated, the field
size is 26 · 5.5 mm². The same design is used as a
basis (cf. table 1), that is to say the same object
field radius is corrected. Thus, in both folding

20   variants, the distance h of the object field from the
optical axis (object field distance) is of the same
size.

[071]   As a mechanical criterion for a comparison of

25   the two folding variants, let it be assumed that the
smallest distance of the edge of a lens from the object
plane or reticle plane is to be sufficiently large in
order to avoid any detrimental effect on the
construction of the reticle stage. Both folding

30   systems are conceived in such a way that this is
provided in virtually the same way.

[072]   It can be seen that, in the variant shown in
fig. 4 with crossed beam guidance, the constructional-

35   mechanical boundary condition can be met. For this
purpose, it is merely necessary to design the first
lens 152 following the object plane as a cut-off lens,
in order that the second folding mirror 108 does not
collide with this lens or its mount. This is shown in

fig. 2. It can be seen that no beam cutting or vignetting occurs at the folding mirrors 106, 108. In particular, the face of the first folding mirror 106 is sufficiently large that all of the radiation coming

5   from the object can be deflected toward the concave mirror and the reflecting surface of the second folding mirror is sufficient to deflect the entire beam coming from the intermediate image in the direction of the image plane. The beam is not cut by the parts

10 projecting into the beam path either, which contributes in particular to the fact that the region of minimum beam diameter in the vicinity of the intermediate image 102 can be forced through at a distance between the mirror edge closest to the reticle and the reticle.

15

[073]   In the case of conventional folding (fig. 5), on the other hand, for vignetting-free deflection at the first folding mirror, it would be necessary for the latter to pass through the first lens 152'. This can

20 be attributed, inter alia, to the fact that the first folding mirror 106 closest to the object plane is located on the same side as the extra-axial object field. This is precisely the opposite in the case of the folding according to fig. 4, in which the folding

25 mirror nearest to the object (the second folding mirror 108) is located on the side of the optical axis which is opposite the object field. It can further be seen in fig. 5 that the light beams intersect in the vicinity of the tip of the prism which is formed by the mirror

30 edges close to the axis and belonging to the first and second folding mirrors. This would also lead to vignetting and therefore cannot be implemented.

[074]   In order to eliminate the first conflict, it

35 will be necessary for the first folding mirror 106 to be fitted further away from the reticle. However, this would enlarge the folding mirror, as a result of which the second conflict in the vicinity of the prism edge of the folding prism would become even more critical.

As a consequence, the object field must be fitted
further extra-axially and therefore (given an unchanged
size of the superfield) can no longer have the full
field size of 25 · 5.5 mm². It can be shown that,
given the folding geometry shown in fig. 5, only a
field of a size of 16 · 5.5 mm² could be projected
without vignetting, given the same corrected object
field radius (that is to say given the same superfield
size). Here, a great advantage of the beam guidance
according to the invention is shown.

[075] A further embodiment of a catadioptric
projection objective 500 with a geometric beam
splitting, a single concave mirror and a crossed beam
path in 1-folding geometry will be shown using fig. 6.
The basic structure is comparable with the embodiment
of the projection objective 100 according to fig. 2,
for which reason the same designations, increased by
400, will be used for the corresponding features. The
specification of the design emerges from tables 3 and
4.

[076] As distinct from the embodiment according to
fig. 2, an aspheric lens with substantially no
refractive power is arranged between the object plane
501 and the first folding mirror 506. The entry to the
objective is formed by a plane-parallel plate 551 and
the low refractive power asphere 551' following the
latter. In the beam path, which is passed through
twice, between the first folding mirror 506 and concave
mirror 505, the positive refractive power in the
vicinity of the intermediate image 502 is provided by
two positive lenses 553, 553' which are arranged at a
distance from each other and which jointly, with two
negative meniscus lenses 554, 555 arranged in front of
the concave mirror, contribute to positioning the
intermediate image 502 between the mirror edge 515,
facing the object, of the first folding mirror and the
object plane. Optically immediately behind the

intermediate image, the second folding mirror 508 is
located, which can be small on account of the proximity
to the intermediate image and can therefore be moved
closer to the object plane. The function of the
5   transfer group T is fulfilled by a single positive lens
556. The focusing group F has, in front of the system
aperture stop 580, a positive meniscus 560 and a
negative meniscus 561 (in each case with an image-side
concave face), a biconvex positive lens 562 and an
10 object-side concave meniscus 563 with a low refractive
power immediately in front of the system aperture stop.
Arranged between the latter and the image plane 503 are
only positive lenses 564 to 567, the last of which is a
planoconvex lens with a flat exit side. The image-side
15 working distance between the flat exit face and the
image plane is set to the value 0. In this design, the
projection objective can be used for contact projection
lithography by means of "solid immersion". With slight
modifications, it can be changed into an immersion
20 system with a finite working distance, whose region
would have to be filled with an immersion medium. If
the working distance is set, for example, to less than
100 nm and therefore only a fraction of the working
wavelength, then this projection system can be adapted
25 to a use in near field lithography, in which evanescent
fields emerging from the exit side of the objective can
be used for imaging.

[077]   In fig. 7, the region of the twofold beam
30 folding and crossed beam guidance of a catadioptric
projection objective 600 having a single concave mirror
and 1-folding is shown. Corresponding elements bear the
same designations as in fig. 2, increased by 500. As
in the preceding embodiments, the radiation coming from
35 the object plane 601 firstly strikes the first folding
mirror 606, which deflects the radiation away from the
optical axis 610 in the direction of the concave mirror
(not shown), which reflects the radiation toward the
second folding mirror 608. The optical components

serving to form the intermediate image 602, which also include a positive lens 652 arranged in the space between object plane and first folding mirror, are designed such that the intermediate image is located in

5   the direction in which the light runs behind the second folding mirror 608, in front of the first lens 656 of the refractive second objective part. The geometric distance of the intermediate image to the inner edge 615, facing the axis, of the first folding mirror, as

10 in the embodiments according to fig. 2, is only a fraction of about 20-30% of the meridonal extent of the intermediate image, so that there is high geometric proximity. As distinct from the previous embodiments, the intermediate image is not arranged in the space

15 between the critical mirror edge 615 and the object plane, however, but approximately at the axial height of the inner mirror edge 615, beside the latter. The crossed beam guidance of the first beam section (between object plane 601 and concave mirror) and of

20 the second beam section (between concave mirror and image plane) with a cross-over region geometrically between the positive lens 652 and the first folding mirror 606, in conjunction with the proximity of the intermediate image to the critical mirror edge 615,

25 permits a high image-side numerical aperture which, in the example, is NA = 0.8. The specification of this design in detail can be taken from the European patent Application EP 1 115 019 A2, whose disclosure content is made the content of this description by reference

30 (cf. fig. 11 there).

[078]   By using fig. 8, it will be explained, by way of example, that the invention can also be used with advantage in other catadioptric projection objectives

35 having a single concave mirror and a single real intermediate image.   The optical structure of the projection objective 700 with respect to sequence and layout of the lenses along the optical axis can be taken from US patent 6,195,213 B1, which in fig. 2 and

table 1 shows a corresponding optical system with conventional h-folding. The disclosure content in this respect is made the content of this description by reference.

5

[079]   The projection objective 700 is built up in such a way that the radiation coming from the object plane 701 firstly strikes the concave mirror 705, from which it is reflected in the direction of the first

10   folding mirror 706.   The latter is arranged with a reflecting surface facing the optical axis 710 such that the radiation is reflected in the direction of a second folding mirror 708, which follows without any interposed lenses and deflects the radiation in the

15   direction of the lenses of the refractive objective part 707. Since the first folding mirror 706 is arranged on the side of the optical axis 710 that is located opposite the refractive objective part 707 and the radiation coming from the object field on its way

20   to the concave mirror initially passes the first deflection mirror 706 on its side facing the second objective part, the second beam section leading from the concave mirror via the folding mirror 706 to the image plane crosses the first beam section leading from

25   the object plane to the concave mirror in a cross-over region, which is located between the first and second folding mirror in the vicinity of the first folding mirror 706. The intermediate image 702 is produced immediately in front of the first folding mirror.

30

[080]   The crossed beam guidance in the case of h-folding has a number of advantages as compared with the conventional arrangement of the folding mirrors.   From the point of view of mounting technology and mechanics,

35   it is beneficial that the first folding mirror 706 is located on the side of the optical axis 710 facing away from the second objective part 707. As a result, a stable fixing is possible with the aid of a compact fixing construction fitted to the rear side of the

mirror on a mounting element which can be fitted stably
with the lens mounts of the optical components located
in front of and behind the first folding mirror. From
a mechanical-optical point of view, care must be taken
5   that, in the crossed beam guidance according to the
invention, the first folding mirror in relation to the
part of the optical axis running between the object
plane and concave mirror is on the side facing away
from the second objective part 707, which corresponds
10   to an arrangement of the first folding mirror on the
(lower) side, facing away from the object plane, of the
horizontal section 710' of the optical axis between the
first folding mirror and the second folding mirror. In
the case of the beam guidance according to the
15   invention, this horizontal part 710' of the optical
axis can be brought considerably closer to the reticle
plane than in the case of conventional h-folding, in
which the horizontal part of the optical axis is
located geometrically between the first folding mirror
20   and the concave mirror, that is to say on the side of
the first folding mirror facing away from the reticle.
By displacing the horizontal part of the optical axis
in the direction of the object plane, a reduction in
the geometric optical conductance (etendue) can be
25   achieved, since the critical (inner) edge of the
folding mirror can be brought closer to the reticle
plane.

[081]   By using the following figures, exemplary
30   embodiments of catadioptric projection objectives
according to the invention having more than one real
intermediate image and more than one concave mirror
will be explained. These are distinguished, inter alia,
by the fact that, with a beneficial design, they permit
35   good correction of image errors, in particular it being
possible to achieve effective correction of the Petzval
sum (that is to say the image field curvature) and
chromatic aberrations under conditions which are
beneficial to fabrication.

[082]   Fig. 9a shows an embodiment of a projection objective according to the invention having two catadioptric objective parts, two refractive objective parts and precisely three real intermediate images. Fig. 9b shows a detailed view of the region of the beam deflection device (folding device). The crossed beam path can be seen particularly well in this illustration.

[083]   The immersion projection objective 800 has between its object plane 801 and the image plane 803, in this order, a first dioptric objective part 805, a first catadioptric objective part 806 having a first concave mirror 807 and an associated folding mirror 808, a second catadioptric objective part 809 having a second concave mirror 810 and an associated folding mirror 812, and also a second refractive objective part 815. From the reticle (object plane 801, shown on the left in the figure), the light passes through the first refractive objective part 805, which forms the first intermediate image 820. After that, the light strikes the first folding mirror 808 in the light passage direction, which is immediately behind the first intermediate image, in the vicinity of the latter, and deflects the light in the direction of the first concave mirror 807. The associated catadioptric objective part 806, which points downward in the drawing, can be aligned substantially horizontally in operation. Such objective parts are also designated a horizontal arm (HOA) here. The catadioptric objective part 806 projects the light of the first intermediate image onto a second intermediate image 830, which is located in the vicinity of the first folding mirror 808. More precisely, the second intermediate image is located in the vicinity of an inner mirror edge 811, facing the optical axis 810, of the first folding mirror 808, in the geometric space between this edge and the last lens 812 of the first refractive objective

part 805. From the second intermediate image 830, the
light passes through the second catadioptric objective
part 809, which forms a third intermediate image 840 on
the return path from the concave mirror 810, said image
5   being located immediately in front of the second
folding mirror 812. By means of the second refractive
objective part 815, the third intermediate image 840 is
projected directly, that is to say without a further
intermediate image, onto the wafer arranged in the
10 image plane 803.

[084]   In fig. 9 it is possible to see particularly
well that the beam path 860 leading from the object
plane 801 of the first concave mirror 807, and the
15 second beam path 861 leading from the first concave
mirror 807 to the following objective part and finally
to the image plane, cross in the vicinity of the first
folding mirror 808, approximately in the region of the
first intermediate image. The further course of the
20 beam after the second intermediate image is then free
of any crossing.

[085]   This cross-like structure with two coaxial
concave mirrors has precisely three real intermediate
images. There therefore exist four possible positions
25 for aperture stops bounding beams (real pupil
positions), mainly in the first refractive objective
part 805, in the vicinity of the concave mirrors 807
and 810, and in the second refractive objective part
30 815.   In this specific exemplary embodiment, the
aperture stop 870 is located in the first refractive
objective part.

[086]   The folding mirrors 808, 812 are in each case
35 located in the geometric (physical) vicinity of the
intermediate images, which minimizes the optical
conductance, so that the object field can be arranged
minimally extra-axially. The intermediate images, that
is to say the entire region between the paraxial

intermediate image and the marginal ray intermediate
image, do not lie on the mirror surfaces, however, so
that possible errors in the mirror surfaces are not
projected sharply into the image plane. In this case,

5   the first and the third intermediate images are in each
case located both optically and geometrically in the
immediate vicinity of the most closely situated folding
mirror, while the second intermediate image 830,
although it is located geometrically in the immediate

10   vicinity of the inner mirror edge 811, is located
optically approximately centrally between the concave
mirrors 807 and 810.

[087]   The reflecting surfaces of the folding mirrors

15   in this embodiment are in each case inclined at 45°
with respect to the optical axis, so that the folding
angles are exactly 90°. This rectangular folding is
beneficial to the performance of the reflective layers
of the folding mirrors.

20

[088]   The reticle plane 801 (plane of the object
field) is not affected by the mounting technology. In
particular, there is a large spacing from the concave
mirrors, on account of the first relay system 805. No

25   cut-off lenses are necessary, so that all the lenses
can be formed as round lenses.

[089]   The specification of the design is summarized
in tables 5 and 6 in tabular form and conventional

30   notation.   The system, designed as a catadioptric
immersion objective, with a full field of $26 \cdot 5.5$ mm^2
and extremely pure water as immersion liquid, reaches
an image-side numerical aperture NA = 1.3.   The
projection objective per se is not aperture-limited,

35   since there is beneficial folding geometry with an
intermediate image in the vicinity of a folding mirror.
Higher apertures, for example NA = 1.35 or NA = 1.4 or
NA = 1.5 or NA = 1.7, are available if more highly
refractive immersion media are used. The diagonal ratio

between the length of a diagonal of a minimum circle centered in relation to the optical axis and enclosing the object field and the length of a diagonal of the object field (cf. fig. 3) is about 1.17. The wavefront aberrations are 7.5 mλ. In embodiments for 193 nm, all the lenses consist of silicon dioxide. The optically free lens diameters are considerably less than 300 mm. The mass of the raw material (raw compound) necessary for lens production is lower as compared with conventional refractive systems or conventional catadioptric systems mentioned at the beginning having h-folding or 1-folding, which represents a considerable improvement.

[090]   In the following text, further special features will be indicated which, in each case individually or in combination with other features, can be beneficial in this and in other embodiments. The design contains four field lenses or field lens systems 812, 885, 886/887, 888 with a positive refractive power, which are in each case arranged in the immediate vicinity of the folding mirrors and the intermediate images. In at least one of the catadioptric horizontal arms, there should be a negative lens, in order to ensure the chromatic correction. Preferably, at least one negative lens 890, 891, 892 is provided in each catadioptric objective part, preferably in the immediate vicinity of the concave mirror. Beneficial variants include at least three lenses which are passed through twice. In the exemplary embodiment shown, there are six lenses which are passed through twice, namely the field lenses 885, 886, 887 and the negative lenses 890, 891, 892 in front of the concave mirrors for the chromatic correction of the longitudinal color error.

[091]   Beneficial variants include little negative refractive power in the refractive objective parts, which means that the lens diameters of these parts can be kept small overall. In the exemplary embodiment,

only in the second refractive objective part 815 is a
biconcave negative lens 880 provided in the divergent
beam path on the input side of the objective part, at
the exit side of which high angles of incidence
5   beneficial to the correction occur.

[092]   The   design   exhibits   high   coma   in   the
intermediate   images,   in   particular   in   the   third
intermediate image 840. This helps to correct the sine
10 condition in the image space without surfaces with
excessively high angles of incidence in the second
refractive objective part 815.

[093]   Numerous   variants   are   possible.   In   this
15 regard, fig. 10 shows, by way of example, an optically
identical variant of a projection objective 800′ having
catadioptric subsystems inclined obliquely with respect
to the optical axis for more beneficial reflecting
layers. In the embodiment shown, the horizontal arms
20 continue to be coaxial but are inclined by 20° with
respect to a vertical alignment.   The angles of
incidence at the folding mirrors can thus be reduced.

[094]   It   is   also   possible   to   design   projection
25 objectives   according   to   the   invention   as   a   dry
objective.   Fig.   11   shows,   by   way   of   example,   a
projection objective 900 having an image-side numerical
aperture NA = 0.95 and a finite working distance at the
wafer. In dry systems, the space between the objective
30 exit face and the wafer is filled with a gas during
operation.   System data for the cross-like dry system
in fig. 11 is specified in tables 7 and 8.   In this
system, at individual surfaces of the second refractive
objective part, in particular at the exit face of the
35 input-side biconcave negative lens and at the exit face
of the object-side concave negative meniscus lens, very
high angles of incidence, which contribute effectively
to the correction, occur in the immediate vicinity of
the pupil face situated most closely to the image.

[095]   The embodiments shown in figures 9 to 11 are
designed such that the two flat folding mirrors are
positioned at a short distance from each other, back to
back, that is to say with reflecting surfaces facing
away from each other.   Under certain circumstances,
this can be achieved by means of a single, double-
silvered element which can have the form of a plane-
parallel plate. In principle, it is also possible for
the beam deflection to be carried out with a solid
material prism, as shown in fig. 12.   In this case, the
light coming from the object plane firstly enters the
folding prism 895 and the first folding reflection
takes place at the hypotenuse face 896 of the prism.
After passing through the first catadioptric objective
part and the second catadioptric objective part, the
second folding reflection takes place at the same
hypotenuse face, but on its rear side.   In the
embodiment shown in fig. 12, a first beam path leads
from the object plane (not shown) via the first folding
mirror (inner side of the hypotenuse face) and the
first concave mirror (not shown, arranged at the bottom
in the figure) to the second second concave mirror (not
shown, located at the top in the figure), and the
second beam section, after reflection at the second
concave mirror, leads via the second folding mirror
(outer side of the hypotenuse face) in the direction of
the image plane.   In this case, the crossing of the
beam paths takes place immediately after the reflection
at the second folding mirror and the formation of the
third intermediate image, in the immediate vicinity of
the reflecting surface of the second folding mirror,
between the latter and the first lens of the following,
second refractive objective part.

[096]   For the case in which calcium fluoride is
selected for the deflection prism, for reasons of laser
resistance, care must be taken that, its refractive
index of n ≈ 1.50 at 193 nm and the numerical aperture

of about NA = 0.3 present at the intermediate image,
total reflection over the entire beam cross section is
not to be expected. It is therefore beneficial to apply
a powerful reflective layer, reflecting on both sides,
to the hypotenuse face. However, it is also possible
to enlarge the folding angle in the prism in such a way
that total reflection occurs at the hypotenuse face for
all incident rays. It is then possible to dispense with
a reflective coating.

[097]   Within the scope of this cross-like design,
numerous variants are possible.   For example, it is
possible to provide different projection scales, for
example reduction scales of 4:1, 5:1 or 6:1.   Higher
projection scales (for example 5:1 or 6:1) can be more
beneficial, since they reduce the object-side aperture
and can thus relax the requirements on the folding
geometry.

[098]   The first refractive subsystem, serving as a
relay system, which forms the first intermediate image,
has a projection scale β close to 1 in the exemplary
embodiments. However, this is not imperative.   It is
equally not very necessary for the catadioptric
objective parts to have projection scales in the region
of 1.   Here, a magnifying projection scale of the first
objective part can be beneficial to relaxing the
requirements on the folding geometry.

[099]   In the above examples of catadioptric systems
having three intermediate images and two catadioptric
subsystems, the refractive front system (first
subsystem, relay system) is constructed asymmetrically.
The distance between the two planar folding mirrors
should be small, in order that the distance of the
extra-axial object field from the optical axis remains
as small as possible with vignetting-free projection,
and thus reduce the requirements on the optical design
for achieving a small etendue or a small superfield.

In addition, the object-image shift (OIS), that is to say the lateral offset between the object-side optical axis and image-side optical axis, then remains small.

5   [0100] By using fig. 13, a variant of a cross-like catadioptric system 1000 having two concave mirrors and three intermediate images will be shown, being distinguished by a largely symmetrical structure. It has, between its object plane 1001 and its image plane
10   1002, a first refractive objective part 1010, which forms a first intermediate image 1011, a first catadioptric objective part 1020, which forms a second intermediate image 1021 from the first intermediate image, a further catadioptric objective part 1030,
15   which forms a third intermediate image 1031 from the second intermediate image, and a fourth, refractive object part 1040, which projects the third intermediate image into the image plane 1002. All the objective parts have a positive refractive power. Lenses or lens
20   groups with a positive refractive power are represented by double arrows with points aimed outward, lenses or lens groups with a negative refractive power, on the other hand, are represented by double arrows with points aimed inward.

25

[0101] A first beam section 1050 runs from the object plane 1001 via the first folding mirror 1055 and the associated concave mirror 1025 following in the light path to the concave mirror 1035 of the second
30   catadioptric objective part 1030. A second beam section 1060 runs from this concave mirror 1035 via the second folding mirror 1065 to the image plane. On the way from the second folding mirror to the image plane, the second beam section crosses the first beam section in
35   the region in front of the reflecting surface of the second folding mirror.

[0102] The first objective part 1010 comprises a first lens group LG1 with a positive refractive power and a

second lens group LG2 with a positive refractive power. Between these two lens groups, the main beam intersects the optical axis at the point of a preferred aperture stop plane (system aperture stop) 1070.

[0103] The first lens group LG1 preferably comprises at least two positive lenses, namely at least one lens L1 close to the field and at least one lens L2 close to the aperture. This applies in a corresponding way to the lens group LG2, which preferably has at least one lens L4 close to the field and at least one lens L3 close to the aperture.

[0104] Meeting the following conditions, individually or in combination, can be beneficial to simplifying the fabrication of the system:
LG1 = LG2; L1 = L2 = L3 = L4; L1 = L4; L2 = L3.

[0105] In these equations, the equality of two lenses is to be understood to mean equality of their radii. The lenses can therefore have unequal thicknesses. The equality of radii is not to be understood to be mathematically exact but, from a fabrication point of view, that the lens faces should be capable of production with the same tool. For the equality of lens groups, appropriate boundary conditions apply. Such systems offer advantages in fabrication, since the production and testing of the lenses are simplified.

[0106] The arrangement of the lenses can be symmetrical or asymmetrical in relation to planes perpendicular to the optical axis. Here, a symmetrical structure with reference to the aperture stop plane 1070 is beneficial. In advantageous embodiments, the aperture stop is fitted in this aperture stop plane for the purpose of variable limiting of the beam diameter. This is beneficial since, as a result, no asymmetrical image errors are introduced into the first intermediate image 1011.

[0107] The projection scale β of the first objective part 1010 can be about β = 1. Although the first subsystem 1010 is constructed largely symmetrically, it is operated asymmetrically, that is to say with β ≠ 1. The advantage of this quasisymmetrical arrangement is the introduction of a value which is advantageous for the further correction of the chromatic magnification difference (transverse color error), and other asymmetrical image errors, primarily coma.

[0108] The objective can have one or more aspherical faces. The lens L1 arranged close to the field preferably bears at least one aspherical face in order to correct the telecentering in the object space. Alternatively or additionally, one of the lenses L3 and/or L4 can bear at least one aspherical face in order to correct the spherical aberration in the first intermediate image. This relieves the folding geometry stress and permits a small etendue (optical conductance).

[0109] The first objective part 1010 is preferably constructed with "a low Petzval", that is to say with lenses with a reduced Petzval sum. A "low Petzval" structure can be produced if lenses with a small Petzval sum are employed, in particular suitable meniscuses. The telecentering, spherical aberration and astigmatism can be corrected by means of aspheres on the lenses L1 and L2 or L3 and L4.

[0110] In general, in these and in the other embodiments, the optical distance between a reflecting surface of a folding mirror and the most closely situated intermediate image should lie between a finite minimum distance and a maximum distance. The maximum distance can, for example, be 1/10 or 1/15 or 1/20 of the system length (overall length, distance between

object plane and image plane).   The minimum distance
should be small in comparison with this.

[0111] It is beneficial if the first objective part
5   1010 is over-corrected spherically if the first folding
mirror   1055   is   situated   behind   the   paraxial
intermediate   image   1011,   and   is   under-corrected
spherically   if   the   paraxial   intermediate   image   is
situated behind the folding mirror.   This ensures that
10   the intermediate image does not lie on the reflecting
surface.

[0112]   The Petzval sum is preferably set such that the
focus of the outermost field point and of the innermost
15   field point are located virtually at the same distance
from the first folding mirror. The intermediate image
can   then   be   moved   close   to   the   reflecting   surface,
since   the   curved   image   field   curves   away   from   the
reflecting   surface.   This   relaxes   the   requirements   on
20   the folding geometry and permits a small etendue.

[0113]   The catadioptric objective parts 1020, 1030 are
preferably   constructed   doubly   telecentrically.   This
permits the correction of the astigmatism in the second
25   and third intermediate image.

[0114]   It   is   possible   that   the   first   objective   part
1010   has   no   negative   lenses.   In   some   embodiments,
provision   is   made   to   correct   the   Petzval   sum   in   the
30   refractive   first   objective   part   1010   as   well   or   to
reduce   it   sharply.   Negative   lenses   close   to   the   object
or   close   to   the   image   can   be   used   for   this   purpose.

[0115]   The catadioptric objective parts 1020, 1030 are
35   preferably   constructed   axially   symmetrically,   so   that
all   the   lenses   are   used   with   a   double   passage.   It   is
beneficial if they stand from a positive lens group LG4
or   LG5   in   the   vicinity   of   the   corresponding
intermediate   image,   and   a   negative   lens   group   LG3   or

LG6 in the vicinity of the concave mirror.   The
positive lens groups LG4, LG5 preferably have one or
two positive lenses, the negative lens groups LG6, LG3
have a maximum of three negative lenses.   In some
5 embodiments, it is possible to dispense with negative
lenses in one of the catadioptric objective parts.

[0116] A symmetrical structure of the catadioptric
parts can be beneficial.   It is preferable if,
10 according to the above explanations, the following
conditions are met, alternatively or in combination:
LG4 = LG5; LG3 = LG6; and M1 = M2, where M1 and M2 are
the concave mirrors 1020, 1035. The equality of the
optical components is to be understood in the sense of
15 the above definition of equality of radii. In the case
of a symmetrical structure, the aberration load
(Petzval and longitudinal color error CHL) is
distributed substantially uniformly to the two
catadioptric objective part. This structure can be very
20 advantageous, since the refractive powers and, as a
result, the aberration contributions can be minimized.

[0117] It can be beneficial to operate the
catadioptric objective parts 1020, 1030 quasi-
25 symmetrically, that is to say with a projection scale
differing slightly from β = 1.   This permits simple
correction of the transverse color error (CHV) for the
overall system.

30 [0118] In another preferred arrangement, the positive
lens groups LG4, LG5 each comprise two positive lenses,
which can in particular be identical.   This relaxes the
requirements on the aberration contributions of these
lens groups.
35

[0119] It can be beneficial if the catadioptric
objective parts 1020, 1030 are constructed such that
the Petzval sum of the refractive lens elements of the
lens groups LG3 and LG4 in the first catadioptric

objective part 1020, and LG5 and LG6 in the second
catadioptric objective part 1030 compensate one
another, largely or completely. Then, the Petzval
contribution of the concave mirrors 1025, 1035
5   primarily remains for the compensation of the Petzval
curvature of the objective parts.

[0120] In the catadioptric parts, one or more
aspherical faces can be provided. This permits or
10   assists a correction in the second and third
intermediate image, and thus permits relaxation of the
requirements on the folding, and also a reduction in
the optical conductance.

15   [0121] The refractive objective part 1040 is
preferably constructed from three lens groups, namely a
first lens group LG7 close to the field and a second
and third lens group LG8 and LG9, between which the
main beam cuts the optical axis, so that a preferred
20   aperture stop plane is produced here. Lens group LG8 in
front of the system aperture stop preferably has at
least one face curved toward the image plane with high
beam angles, for example an image-side lens face of a
negative meniscus lens or a negative biconcave lens.
25   This contributes substantially to the correction of the
sine condition. No lens group should be arranged
between the aperture stop position and the image plane,
that is to say in the lens group LG9. It is beneficial
if the last two or more lens elements consist of
30   calcium fluoride with various crystal orientations, by
which means compaction problems can be avoided and, at
the same time, influences of the intrinsic
birefringence can at least partly be compensated for.

35   [0122] The two plane-parallel folding mirrors 1055,
1065 can be provided on a single plane-parallel plate
reflective on both sides. This should consist of a
highly transparent material. This permits simple
testing of the parallelism before coating with

reflective layers. Preferred material for the substrate is silicon dioxide. As a result of a small distance between the folding mirrors, a reduction in the objective etendue (and in the object image shift) is

5   possible.

[0123] Within the scope of the invention, systems having more than three intermediate images are also possible. As a result, further degrees of design

10   freedom for optimizing the space required and the optical correction can be created. The projection objective 1100 in fig. 14 has between its object plane 1101 and the image plane 1102 a first refractive subsystem 1110 for forming a first real intermediate

15   image 1111, a first catadioptric objective part 1120 for forming a second real intermediate image 1121 from the first intermediate image, a second refractive subsystem 1130 for forming a third intermediate image 1131 from the second intermediate image, a further

20   catadioptric objective part 1140 for forming a fourth intermediate image 1141 from the third intermediate image, and a third refractive objective part 1150 which projects the fourth intermediate image into the image plane 1102. The first catadioptric objective part 1120

25   comprises a first folding mirror 1122 for deflecting the radiation coming from the object in the direction of the concave mirror 1125, and the second catadioptric objective part 1140 has a folding mirror 1142 which is assigned to the concave mirror 1145 and deflects the

30   radiation coming from the concave mirror 1145 in the direction of the image plane.

[0124] In the region of the first catadioptric objective part, a first beam section 1160 leads from

35   the object plane via the first folding mirror 1122 to the concave mirror 1125, and a second beam section 1170 leads from the latter to the following objective parts. The two beam sections cross one another in the vicinity of the object-side mirror edge, facing the first

objective part 1110, of the folding mirror 1122. A
symmetrical situation results in the second
catadioptric objective part 1140. The radiation passing
from the object plane to its concave mirror 1145 forms
5   a first beam section 1170, the radiation reflected from
the mirror 1145 and deflected by the plane mirror 1142
in the direction of the image plane forms a second beam
section 1180, which crosses the first beam section in a
cross-over region between the folding mirror 1142 and
10 refractive subsystem 1150.   The overall projection
objective can have substantially a point-symmetrical
structure, in which the point of symmetry lies within
the central relay system 1130.

15 [0125] The entry-side and exit-side refractive systems
1110 and 1150 in each case have a projection scale β ≈
1, and this is also true of the catadioptric objective
parts 1120 and 1140. The refractive relay system 1130,
which transfers the radiation from the first
20 catadioptric subsystem 1120 to the second catadioptric
subsystem 1140 with a projection, has a projection
scale in the region of 1:3 to 1:6. This reduction also
corresponds to the overall reduction of the projection
objective.   In the basic structure refractive -
25 catadioptric - refractive - catadioptric - refractive,
the axial orientation can be set as required by means
of suitable alignment of the folding mirrors.

[0126] The aberration compensation proceeds in a
30 similar way to that in the preceding examples. The
series of continuous lines corresponds to the main ray
of the outer field point.

[0127] In the system in fig. 14, the optical axes of
35 the catadioptric subsystems 1120 and 1140 run
coaxially, so that an inclination of one of the axes
defines the inclination of the other axes. If, for
example, one axis is inclined in order to create space,
the other axis may also be inclined such that space is

restricted. In the following text, exemplary
embodiments of how such problems can be avoided will be
shown. They can be used as self-contained projection
objectives or as subsystems within a more complex
5   catadioptric structure.

[0128] From the point of view of the basic structure,
the projection objective 1200 in fig. 15 represents a
combination of a catadioptric projection objective 1210
10   with 1-folding and two folding mirrors fitted to a
mirror prism (cf. fig. 5) and a following catadioptric
subsystem 1220 with modified 1-folding and crossed beam
path (for example according to fig. 4). The first
catadioptric subsystem 1210 forms a real intermediate
15   image 1202 from the extra-axial field, which is
arranged in its object plane 1201. This intermediate
image is projected into the image plane 1203 of the
system by the second catadioptric subsystem 1220.

20   [0129] The object plane 1201 of the system shown can
be the object plane of the entire projection objective
or an intermediate image plane, in which there is
situated an intermediate image which is formed by a
subsystem connected upstream but not shown in fig. 15.
25   Fig. 16 shows, by way of example, such a structure,
which is provided in a refractive subsystem 1250,
serves as a relay system and forms a real intermediate
image of the object plane 1290 in the plane 1201. This
is used as the object of the following catadioptric
30   system according to fig. 15, which comprises two
axially offset concave mirrors.

[0130] In both the embodiments, a first beam section
leads via multiple folding to the concave mirror 1221
35   of the second catadioptric objective part 1220, while a
second beam section runs from this mirror via the
second folding mirror 1242 to the image plane 1203. In
the geometric space between the exit-side folding
mirror 1212 of the first catadioptric objective part

and the first folding mirror 1222 of the second catadioptric objective part 1220, the first beam path and the second beam path cross behind the intermediate image 1202.

5

[0131] The projection system shown in fig. 15, which can be a self-contained projection objective or a subsystem within a larger projection objective (cf. fig. 16), has two real intermediate images 1202, 1232. The optical axes of the catadioptric objective parts 1210, 1220 are decoupled from each other, that is to say are not coaxial with each other but offset laterally parallel to each other. The catadioptric subsystems are in each case constructed axially symmetrically. Each includes a positive lens group close to the object and a negative lens group close to the concave mirror. Therefore, positive refractive power is arranged in the vicinity of the intermediate images and of the folding mirrors here too, while negative refractive power is concentrated in the vicinity of the concave mirrors.

[0132] As shown in fig. 16, the subsystem illustrated in fig. 15 can be used to project the intermediate image of the object field formed by a relay system 1250 into the image plane of the projection objective. The overall system then has three intermediate images.

[0133] Another variant provides that, in this system, the optical axes of the mirror groups can both be inclined in the direction of the wafer plane. This increases the space between the concave mirror of the first catadioptric objective part and the reticle plane or intermediate image plane 1201.

35

[0134] All the embodiments illustrated by way of example can be incorporated in the projection exposure machine shown in fig. 1 instead of the projection objective 5. In the case of wafer scanners, care must

be taken that the drive for the movements of the device 40 for holding and manipulating a mask (reticle stage) and the device 50 for holding and manipulating the wafer (wafer stage) must be matched to the type of catadioptric projection objective. Depending on the number of folding mirrors, concave mirrors and intermediate images, the drive must be configured such that either a scanning movement of reticle and wafer stage in the same direction or a movement of reticle and wafer stage in opposite directions takes place during scanning. If the sum S of the number Z of intermediate images, the number F of folding mirrors and the number K of concave mirrors is an uneven number, then a scanning movement in the same direction must precede; if the sum S is an even number, then a scanning movement in opposite directions must be produced. Therefore, in the embodiments explained by using figures 9, 10, 11, 12, 13 and 16, a scanning movement in the same direction must be provided, while in the embodiments according to figures 2, 6, 7, 8, 14 and 15, reticle and wafer must be moved in opposite directions in relation to each other along the y axis.

Table 1

Face	Radii	Thicknesses	Material	Index	½ diameter
1	0,000000	0,000000	AIR		79,675
2	0,000000	10,000000	SIO2HL	1,56018811	79,675
3	0,000000	1,000000	AIR		81,476
4	319,475286	20,000234	SIO2HL	1,56018811	85,084
5	995,269474	68,424969	AIR		85,919
6	0,000000	169,872505	AIR		95,577
7	-970,753457	44,999585	SIO2HL	1,56018811	119,609
8	-327,540786	217,911147	AIR		123,649
9	-231,387741	17,500000	SIO2HL	1,56018811	125,416
10	-1065,062890	48,294619	AIR		135,575
11	-196,821494	17,500000	SIO2HL	1,56018811	136,404
12	-525,772724	32,979078	AIR		160,520
13	0,000000	0,000000	REFL		204,292
14	264,796887	32,979078	REFL		162,687
15	525,772724	17,500000	SIO2HL	1,56018811	160,034
16	196,821494	48,294619	AIR		132,915
17	1065,062890	17,500000	SIO2HL	1,56018811	130,452
18	231,387741	217,911147	AIR		117,791
19	327,540786	44,999585	SIO2HL	1,56018811	101,599
20	970,753457	181,477269	AIR		96,159
21	0,000000	128,395393	AIR		61,789
22	0,000000	24,998738	AIR		110,784
23	312,774233	50,000130	SIO2HL	1,56018811	135,026
24	-938,039680	2,332118	AIR		135,592
25	715,324368	28,435222	SIO2HL	1,56018811	135,878
26	-1554,047709	0,949762	AIR		135,289
27	626,921957	28,002516	SIO2HL	1,56018811	132,433
28	-1428,035483	37,991193	AIR		130,956
29	-309,156200	9,521188	SIO2HL	1,56018811	125,631
30	-562,362375	181,567266	AIR		125,277
31	-173,995248	9,499422	SIO2HL	1,56018811	99,321
32	247,888809	29,437283	AIR		109,165
33	8340,117725	32,129675	SIO2HL	1,56018811	111,460
34	-312,940978	7,464540	AIR		116,082
35	929,377252	44,625129	SIO2HL	1,56018811	132,361
36	-333,512913	0,949477	AIR		134,568
37	591,097249	44.418308+C2	SIO2HL	1,56018811	140,004
38	-1614,017804	24,278142	AIR		140,003
39	0,000000	-23,329538	AIR		138,515
40	302,573027	9,498538	SIO2HL	1,56018811	139,988
41	225,452829	23,324104	AIR		137,709
42	374,450165	43,305784	SIO2HL	1,56018811	138,658
43	-1347,892608	0,947859	AIR		139,026
44	302,595256	44,140336	SIO2HL	1,56018811	139,127
45	-12394,382724	0,947473	AIR		137,426
46	220,761542	40,029388	SIO2HL	1,56018811	125,456
47	809,070272	0,946947	AIR		121,419
48	163,063737	40,300977	SIO2HL	1,56018811	103,421
49	762,111474	0,946425	AIR		96,933
50	139,902742	77,435206	SIO2HL	1,56018811	75,207
51	0,000000	2,000000	H2OV193	1,43667693	19,413
52	0,000000	0,000000	AIR		17,000

Table 2

	5	8 = 19	10 = 17	12 = 14	27
K	0	0	0	0	0
C1	-1,188191E-08	3,591288E-09	-4,791180E-09	-8,429951E-10	-5,683539E-09
C2	1,967391E-13	-3,350971E-14	6,912483E-14	-5,232984E-15	6,541643E-15
C3	-7,746732E-18	1,502596E-18	2,275816E-19	-3,132061E-19	-2,750649E-19
C4	4,382264E-23	2,954168E-23	1,312434E-22	-2,344674E-23	5,788139E-23
C5	4,532193E-26	-6,493001E-28	-4,748900E-27	6,334947E-28	-2,220373E-27
C6	-3,233502E-30	3,320789E-32	1,399914E-31	-1,231728E-32	8,916186E-32

	33	35	37	47	
K	0	0	0	0	
C1	-8,560622E-09	-2,328354E-08	1,335791E-09	-1,418195E-08	
C2	-1,349963E-12	2,144034E-12	-8,056724E-13	1,409773E-12	
C3	1,587936E-16	-1,398657E-16	4,148247E-17	-6,196993E-17	
C4	-8,008240E-21	5,252748E-21	-9,137514E-22	1,830118E-21	
C5	2,874374E-25	-1,188241E-25	1,616592E-26	-3,946542E-26	
C6	-6,218920E-30	1,696094E-30	-2,274089E-31	2,728014E-31	

Table 3

Face	Radii	Thicknesses	Material	Index	½ diameter
1	0,000000	0,000000	AIR		74,869
2	0,000000	10,000000	SIO2	1,56097018	74,869
3	0,000000	0,500000	AIR		76,658
4	3088,172820	10,000000	SIO2	1,56097018	76,952
5	0,000000	60,000000	AIR		78,641
6	0,000000	0,000000	AIR		95,735
7	0,000000	134,465366	AIR		95,735
8	302,601867	34,401664	SIO2	1,56097018	144,675
9	705,234819	68,979243	AIR		144,202
10	251,382127	33,175965	SIO2	1,56097018	149,996
11	426,058169	289,332591	AIR		147,417
12	-260,112697	20,000000	SIO2	1,56097018	121,372
13	-572,625245	42,216988	AIR		125,407
14	-171,019518	20,000000	SIO2	1,56097018	125,493
15	-855,924382	37,063295	AIR		149,787
16	0,000000	0,000000	REFL		192,254
17	264,447259	37,063295	REFL		151,718
18	855,924382	20,000000	SIO2	1,56097018	150,217
19	171,019518	42,216988	AIR		124,976
20	572,625245	20,000000	SIO2	1,56097018	124,607
21	260,112697	289,332591	AIR		118,964
22	-426,058169	33,175965	SIO2	1,56097018	123,141
23	-251,382127	68,979243	AIR		125,542
24	-705,234819	34,401664	SIO2	1,56097018	114,138
25	-302,601867	148,236577	AIR		113,753
26	0,000000	76,228794	AIR		65,370
27	0,000000	0,000000	AIR		87,565
28	0,000000	201,841415	AIR		87,565
29	1761,166817	50,475596	SIO2	1,56097018	148,012
30	-358,244969	284,608494	AIR		149,872
31	303,934833	35,000000	SIO2	1,56097018	147,098
32	509,533530	7,170752	AIR		143,625
33	370,904878	20,000366	SIO2	1,56097018	142,151
34	211,313761	62,331548	AIR		133,109
35	290,910582	56,153178	SIO2	1,56097018	138,951
36	-1106,757797	68,197851	AIR		137,608
37	-178,117460	59,999881	SIO2	1,56097018	133,318
38	-214,351289	-12,849220	AIR		148,117
39	0,000000	24,486144	AIR		141,938
40	277,046273	63,368104	SIO2	1,56097018	144,287
41	-757,891281	0,999992	AIR		142,301
42	127,447162	72,144248	SIO2	1,56097018	110,531
43	316,261462	0,099994	AIR		92,548
44	137,334842	47,277234	SIO2	1,56097018	81,195
45	210,414165	0,999989	AIR		54,341
46	110,455126	44,071322	SIO2	1,56097018	48,586
47	0,000000	0,000000	SIO2	1,56097018	16,000
48	0,000000	0,000000	AIR		16,000

5

Table 4

Face	4	8 = 25	11 = 22	13 = 20	29	31
K	0	0	0	0	0	0
C1	-1,17E-08	7,10E-10	4,43E-09	-7,25E-09	2,55E-10	9,67E-09
C2	-5,58E-14	1,16E-14	-4,74E-14	2,48E-14	-6,17E-14	-7,64E-13
C3	-6,44E-18	8,33E-19	1,40E-18	1,28E-20	-6,21E-20	1,96E-17
C4	-4,47E-23	-4,54E-23	-5,27E-24	-1,12E-22	2,57E-23	-7,03E-22
C5	-7,31E-27	1,09E-27	-6,31E-28	8,33E-27	-4,83E-28	1,82E-26
C6	3,72E-32	-1,31E-33	2,42E-32	-1,64E-31	-1,36E-33	1,31E-31

Face	33	35	40	43	45	
K	0	0	0	0	0	
C1	-3,12E-08	9,65E-09	-7,80E-09	3,26E-08	8,42E-08	
C2	1,51E-12	-6,13E-13	1,23E-13	-5,62E-13	1,69E-11	
C3	-2,25E-17	8,81E-18	-3,25E-19	4,68E-17	-1,72E-16	
C4	-8,50E-23	3,92E-23	-6,27E-25	-1,11E-20	5,74E-19	
C5	1,19E-26	-5,57E-27	-3,07E-27	6,32E-25	-7,64E-23	
C6	-6,28E-31	8,11E-32	5,63E-32	-8,86E-30	1,33E-26	

Table 5

Face	Radii	Thicknesses	Material	Index	½ diameter
0	0.000000	40.000000			63.000
1	0.000000	0.000000			74.812
2	280.911554	29.101593	SIO2	1.56029525	78.206
3	1315.382634	67.564457			79.868
4	1226.076021	36.889857	SIO2	1.56029525	94.337
5	-224.620142	132.650952			95.649
6	132.557450	37.873616	SIO2	1.56029525	81.937
7	-1652.923938	26.883045			78.866
8	0.000000	138.896699			67.638
9	175.542348	36.333740	SIO2	1.56029525	75.651
10	-236.570865	100.002684			75.039
11	0.000000	9.995756			59.032
12	0.000000	-81.094895	REFL		110.211
13	-208.565918	-48.990866	SIO2	-1.56029525	104.471
14	517.535257	-176.645431			104.642
15	398.156640	-15.000000	SIO2	-1.56029525	100.231
16	-950.114340	-73.251055			103.344
17	116.287221	-15.000000	SIO2	-1.56029525	104.039
18	473.502609	-41.360609			140.152
19	194.854755	41.360609	REFL		143.288
20	473.502609	15.000000	SIO2	1.56029525	139.289
21	116.287221	73.251055			99.401
22	-950.114340	15.000000	SIO2	1.56029525	92.823
23	398.156640	178.645431			87.639
24	517.535257	48.990866	SIO2	1.56029525	84.803
25	-208.565918	81.097016			83.851
26	0.000000	84.970261			59.404
27	176.145326	23.179878	SIO2	1.56029525	79.591
28	756.736803	0.944155			79.800
29	314.641675	30.039119	SIO2	1.56029525	80.579
30	-500.071834	218.126390			80.744
31	-108.651460	15.000000	SIO2	1.56029525	80.556
32	-785.250977	30.057005			106.274
33	-182.598151	-30.057005	REFL		109.565
34	-785.250977	-15.000000	SIO2	-1.56029525	107.546
35	-108.651460	-218.126390			87.013
36	-500.071834	-30.039119	SIO2	-1.56029525	88.079
37	314.641675	-0.944155			87.604
38	756.736803	-23.179878	SIO2	-1.56029525	86.420
39	176.145326	-49.965147			85.965
40	0.000000	-10.012234			62.226
41	0.000000	69.993842	REFL		66.120
42	-340.701792	14.476713	SIO2	1.56029525	61.548
43	-198.092016	38.433493			63.405
44	-681.785807	14.078463	SIO2	1.56029525	69.045
45	-317.005432	27.751722			70.244
46	-110.357531	9.500172	SIO2	1.56029525	70.916
47	311.065100	22.414990			86.590
48	-1344.254472	43.792412	SIO2	1.56029525	90.705
49	-138.390126	5.810077			97.254
50	552.864897	42.476541	SIO2	1.56029525	127.381
51	-483.961511	63.875640			129.334
52	1021.980459	38.430027	SIO2	1.56029525	142.111
53	-410.501933	0.936239			142.917

54	578.822230	39.856519	SIO2	1.56029525	139.665
55	-723.060175	0.932875			138.387
56	283.549462	33.604225	SIO2	1.56029525	124.246
57	1607.080204	0.891917			120.727
58	167.944629	33.588386	SIO2	1.56029525	106.594
59	370.375071	0.941416			101.486
60	94.822236	39.056245	SIO2	1.56029525	80.000
61	175.331402	0.944860			70.631
62	58.889747	49.845949	SIO2	1.56029525	50.337
63	0.000000	2.000000	H2OV193	1.43682260	19.381
64	0.000000	-0.000335	H2OV193	1.43682260	15.750
65	0.000000	0.000335			15.750

Table 6

Face	3	7	9	14 = 24	18 = 20
K	0	0	0	0	0
C1	2.886968E-08	6.178555E-08	-1.273482E-07	-2.178828E-08	1.372393E-08
C2	1.135834E-12	6.960497E-13	4.938210E-12	-2.747119E-13	-3.413863E-13
C3	2.526440E-17	-5.947244E-17	-3.380917E-16	2.007136E-17	1.076781E-17
C4	-2.060922E-21	3.751921E-20	1.794088E-20	1.731842E-21	-3.258468E-22
C5	-7.650561E-25	-4.325897E-24	-7.057449E-25	-2.027055E-25	6.466061E-27
C6	5.723867E-29	7.686244E-29	2.539541E-30	5.423640E-30	-5.896986E-32

Face	28 = 38	32 = 34	48	52	57
K	0	0	0	0	0
C1	7.190084E-08	-3.011106E-08	-5.757903E-08	-3.792122E-08	-2.413143E-08
C2	-5.639061E-13	1.342687E-12	1.903176E-12	1.535276E-12	2.795676E-12
C3	9.086478E-18	-6.959794E-17	-7.267601E-17	-1.992532E-17	-1.365078E-16
C4	8.555051E-22	3.712216E-21	1.940815E-21	-4.676144E-22	5.749863E-21
C5	-2.763206E-26	-1.392566E-25	-1.899677E-25	2.069154E-26	-1.655627E-25
C6	-9.351012E-31	2.691744E-30	-4.747025E-30	-2.314945E-31	2.725293E-30

Table 7

Face	Radii	Thicknesses	Material	Index	½ diameter
0	0.000000	40.000000			63.000
1	0.000000	0.000000			72.900
2	169.031176	30.007246	SIO2HL	1.56029525	77.565
3	172.807988	86.884665			76.339
4	262.433301	42.053156	SIO2HL	1.56029525	100.639
5	-396.930898	170.685368			100.745
6	91.344099	19.740243	SIO2HL	1.56029525	71.904
7	105.469868	16.142176			67.557
8	137.822248	20.121802	SIO2HL	1.56029525	65.141
9	591.277033	20.282197			61.580
10	0.000000	102.718997			54.773
11	344.588322	32.632993	SIO2HL	1.56029525	64.580
12	-119.973712	98.386450			64.972
13	0.000000	10.002615			42.632
14	0.000000	-100.001190	REFL		118.932
15	-248.418133	-48.786808	SIO2HL	-1.56029525	101.847
16	260.257319	-174.240023			102.623
17	751.662806	-15.000000	SIO2HL	-1.56029525	96.605
18	-546.358993	-49.118038			97.378
19	142.990930	-15.000000	SIO2HL	-1.56029525	97.645
20	1260.283293	-34.592380			115.849
21	192.845940	34.592380	REFL		117.242
22	1260.283293	15.000000	SIO2HL	1.56029525	114.937
23	142.990930	49.118038			91.181
24	-546.358993	15.000000	SIO2HL	1.56029525	86.779
25	751.662806	174.240023			82.828
26	260.257319	48.786808	SIO2HL	1.56029525	78.494
27	-248.418133	99.999230			75.744
28	0.000000	95.015900			42.841
29	177.681287	30.008789	SIO2HL	1.56029525	65.929
30	-516.705121	171.287965			67.227
31	217.817800	29.576821	SIO2HL	1.56029525	88.903
32	310.498099	41.618560			86.845
33	-166.352653	15.000000	SIO2HL	1.56029525	86.950
34	439.160019	39.859648			98.417
35	-192.193047	-39.859648	REFL		100.860
36	439.160019	-15.000000	SIO2HL	-1.56029525	99.124
37	-166.352653	-41.618560			87.790
38	310.498099	-29.576821	SIO2HL	-1.56029525	87.638
39	217.817800	-171.287965			89.485
40	-516.705121	-30.008789	SIO2HL	-1.56029525	64.348
41	177.681287	-60.011782			62.727
42	0.000000	-9.997777			44.036
43	0.000000	90.957117	REFL		58.394
44	144.598375	33.191986	SIO2HL	1.56029525	66.065
45	-312.576397	52.726003			66.275
46	-107.389980	9.492973	SIO2HL	1.56029525	62.695
47	165.658290	32.869123			71.558
48	-577.192238	25.782062	SIO2HL	1.56029525	78.414
49	-150.951285	0.976825			84.261
50	29506.35748	24.339009	SIO2HL	1.56029525	100.691
51	-374.391026	0.956935			104.021
52	644.947215	57.187603	SIO2HL	1.56029525	113.079
53	-174.623921	16.895926			114.436

54	1344.546605	39.235791	SIO2HL	1.56029525	103.044
55	-218.318622	12.126286			101.595
56	-165.249581	9.493815	SIO2HL	1.56029525	99.807
57	-529.158535	0.942157			101.677
58	199.277639	44.383379	SIO2HL	1.56029525	100.857
59	-	7.470338			98.182
60	208.537801	18.754883	SIO2HL	1.56029525	85.455
61	334.304631	5.703329			80.986
62	83.732122	29.895330	SIO2HL	1.56029525	65.881
63	175.404465	0.950929			58.182
64	81.491876	26.728679	SIO2HL	1.56029525	51.783
65	443.279667	3.284129			42.929
66	0	10	SIO2HL	1.56029525	39.654
67	0	6			32.119
68	0	0			15.764

Table 8

Face	3	9	11	16 = 26	20 = 22
K	0	0	0	0	0
C1	3.188825E-08	5.249301E-08	-1.523480E-07	-2.416867E-08	2.294396E-08
C2	2.650655E-13	9.672904E-12	6.099552E-12	-5.962244E-13	-1.007737E-12
C3	-6.675542E-17	5.067159E-15	-1.442430E-16	1.303177E-17	5.222514E-17
C4	2.771063E-20	-2.297083E-19	-4.973879E-20	4.998372E-22	-4.373272E-21
C5	-3.914426E-24	4.468892E-23	1.037858E-23	2.854081E-26	2.022375E-25
C6	2.025798E-28	6.699558E-27	-7.916827E-28	-4.246522E-30	-5.622426E-30

Face	30 = 40	36 = 34	48	52	63
K	0	0	0	0	0
C1	7.462841E-08	-6.215300E-08	-1.263170E-07	-3.644419E-08	1.073460E-07
C2	-1.480049E-12	3.990211E-12	1.704645E-12	2.830363E-12	3.012743E-11
C3	7.038597E-18	-2.682924E-16	-1.072376E-16	-6.930387E-17	-1.142275E-15
C4	-6.746798E-21	1.575407E-20	1.095795E-19	-7.697280E-21	2.057679E-19
C5	1.842201E-24	-6.565311E-25	-9.786894E-24	7.864096E-25	1.754484E-23
C6	-1.185318E-28	1.800037E-29	8.828862E-28	-2.506008E-29	3.450730E-27